Charge spreading and position sensitivity in a segmented planar germanium detector

R. A. Kroeger [a], N. Gehrels [b], W. N. Johnson [a], J. D. Kurfess [a], B. P. Phlips [c], and J. Tueller [b]

[a] *Naval Research Laboratory, Washington, DC, USA 20375*
[b] *Goddard Space Flight Center, Greenbelt, MD, USA 20771*
[c] *Universities Space Research Association, Columbia, MD 21044*

The size of the charge cloud collected in a segmented germanium detector is limited by the size of the initial cloud, uniformity of the electric field, and the diffusion of electrons and holes through the detector. These factors affect the minimize size of a practical electrode structure and consequently the position sensitivity. We have completed measurements on a germanium strip detector with a finely collimated gamma ray beam to measure these properties. Preliminary results indicate that the electrons and holes spread by <65 microns over 9 mm drift distance. The experiment was conducted using a germanium strip detector with 25 boron implanted strips on one face and 25 orthogonal lithium drifted strips on the opposite face. The size of the charge cloud is measured by scanning the fan beam between neighboring strips. Results of these experiments suggest that full charge collection on a single strip would be achieved for a majority of events with strip pitch down to ≤300 microns in a 10 mm thick device. Concerns of degradation in the energy resolution due to charge sharing between strips is important for strip pitch much finer than this. There is no evidence of charge loss in hole collection by the boron implanted strips. Applications of a fine pitch germanium strip detector include an imaging focal plane behind a hard X-ray mirror (NASA Constellation mission), or a gamma-ray polarimeter for nuclear physics, amongst others.

1. Introduction

Germanium strip detectors are one of a class of semiconducting detectors which have important applications in astrophysics and gamma-ray imaging [1]. The configuration of the electrodes on these detectors, strip *vs.* individual pixels, is generally selected to suit a particular application or readout electronics. Both configurations have their respective advantages, *i.e.* number of channels, fabrication advantages, and the availability and attachment of appropriate electronics. There are also several important alternatives to germanium, primarily silicon, HgI, CdTe, CdZnTe, and others. The principles of spatial resolution and diffusion of the charge carriers, however, is essentially the same in all of these detectors. In each case, electrons or holes drift through an electric field and are collected by one or several electrodes. Spreading of the charge cloud as it moves through the detector ultimately limits the smallest sized practical electrode structures. Energy resolution is degraded when charge is divided between two or more electrodes. Thus, in many applications the minimum electrode size is limited by diffusion and the charge cloud size.

The size of the charge cloud is determined by several factors. First, the volume is approximated by the range of the primary recoil electron after the initial conversion of a gamma ray [2]. The uniformity of the electric field can have several effects. Non-uniform fields can focus or defocus the charge as it drifts. Further, variations in the impurity concentrations in the detector distort the applied electric field lines [3,4] creating transverse drift fields. This is a smaller effect in Ge with impurity concentrations >100 times smaller than in Si detectors, however Ge detectors are typically much larger volume. Crystal grain boundaries also effect the field uniformity in some detectors such as CdZnTe. Electrostatic repulsion of the charge carriers is a significant factor, especially for larger energy losses (≫60 keV) where the amount of
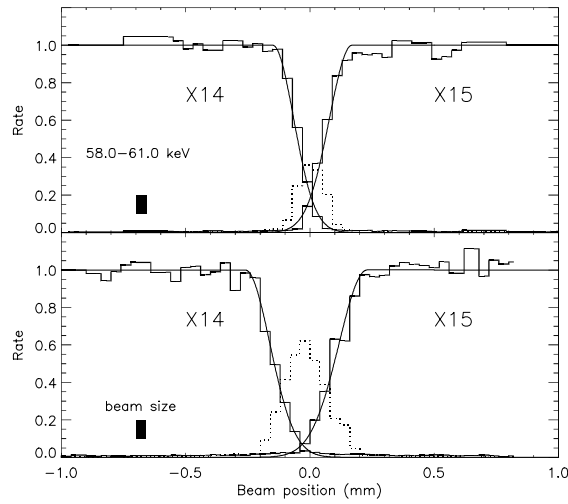
Fig. 1. Response to a 59.5 keV beam *vs.* position in two neighboring boron implanted strips (p^+ contact). Top panel is for beam incident on the p^+ face and the bottom panel is for the beam incident on the opposite face (n^+ contact). Dashed curve shows events that deposit energy in both strips and sum to 59.5 keV.

ionization is quite large (≫20000 e) [5]. Finally, the diffusion of electrons and holes through the detector is important.

Germanium is an ideal detector to study charge diffusion since the impurity concentrations are the lowest of the semiconducting detectors, and fluctuations in the electric field uniformity from variations in impurity concentrations are small.

2. Experiment

Measurements on a germanium strip detector were made with a finely collimated gamma ray beam. The detector is described in ref. [1]. The lateral diffusion of holes and electrons is observed by comparing the spreading of the charge cloud as holes/electrons are drifted 10 mm and 1 mm through the detector respectively and comparing the difference.

The experiment was conducted using a germanium strip detector with 25 boron implanted strips on one face (X-strips) and 25 orthogonal lithium drifted strips on the opposite face (Y-strips). The detector is 10 mm thick with 50 mm long strips distributed on a 2 mm pitch. A fan beam of 59.5 keV gamma rays (^{241}Am) was constructed with a 34 micron width to probe the detector. The beam is oriented along the length of one strip (*e.g.* X14 or Y4), then moved in a sequence of steps until it is fully
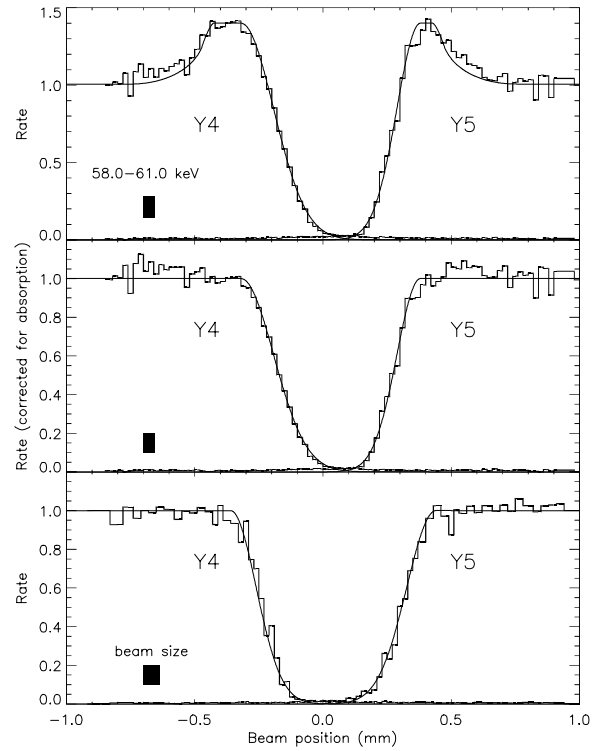
Fig. 2. Response to a 59.5 keV beam *vs.* position in two neighboring lithium diffused strips (n^+ contact). Top and middle panel are for beam incident on the n^+ face. A correction for absorption in the n^+ contact is applied to the middle panel. The bottom panel is for the beam incident on the opposite face (p^+ contact).

over a neighboring strip. Energy is measured by summing the signal from all X-strips (or Y-strips) above threshold (5 keV). Events are selected where the energy measured on both faces of the detector is between 58.0 and 61.0 keV. Energy resolution on each strip is 1.7 keV FWHM.

The effective beam width is slightly larger due to orientation of the fan beam with respect to the strips under study. The orientation of the beam is easily determined by observing the transition from one strip to its neighbor at positions along the length of the strip. The position along the strip is determined by the orthogonal strips on the opposite face of the detector.

Gamma rays have a range of 1 mm at 59.5 keV, thus the majority of interactions are near the surface of the detector. The size of the charge cloud is measured by scanning the fan beam between two of the strips. The full charge cloud is collected entirely on one strip when the fan beam is over that strip (Fig. 1). As the beam moves over the edge, there is a narrow region where charge is shared between the

two neighboring strips. As the beam moves over the next strip, the charge cloud is entirely collected by that strip. The region where charge is shared by the two neighboring strips is governed by the size of the charge cloud and the physical gap between the strips (200 microns in this detector). Boron implanted strips collect holes produced in the interaction.

A similar experiment is performed for electrons collected on the opposite face of the detector (Fig. 2). Electrons are collected on lithium doped electrodes that form an n^+ blocking contact [6]. Lithium is diffused to a depth of 300 microns into the detector. Results for the electrons are more difficult to analyze than for the hole diffusion measurement due to the complex shape of the lithium electrodes. The physical gap between the lithium electrodes is estimated to be 900 microns.

The increase in rate as the beam approaches the edge of the strip is because events that interact in the lithium diffused contact are lost, and the thickness of the contact diminishes from 0.3 mm in the central region, tapering to zero at the edge.. This absorption is easily modeled and corrected (Fig. 2 middle panel).

3. Results

The count rate in a strip as the beam is moved over the edge is well fit by gaussian function with the peak centered on where the response starts to roll off. These fits are the smooth curves shown in Figs. 1 and 2. The half width half maximum (HWHM) of these gaussians are remarkably similar, ranging from 0.10 to 0.15 mm for both boron and lithium contacts. Results are summarized in Table 1. The gap is defined as the distance between the two strip edges at the half-maximum point.

Table 1
Summary of strip edge measurements

Contact	Drift Distance	HWHM X14/Y4	HWHM X15/Y5	Gap
B	10 mm	.10 mm	.11 mm	.11 mm
B	1	.12	.13	.24
Li	10	.15	.11	.44
Li	1	.12	.13	.55

The beam width in these four measurements is 1/3 to 1/4 of the observed HWHM. Errors in the fit curves are ±5 micron HWHM and ±10 micron in the Gap width.

Details of the charge sharing events is beyond the scope of this paper. It should be noted that the combined rate of events plotted in Fig. 1 dips slightly in the gap region between strips with the tight event selection criteria that was used. However, these lost events are recovered when the event selection criteria is relaxed to include events with measured energy between 54.5 and 64.5 keV. The primary reason for this difference is a small number of events that share charge in two strips, but one of the strips is below the detection threshold of ~5 keV. The tight event selection criterion rejects these events, but the looser criterion accepts them.

Charge sharing events collected on the lithium strips (Fig 2) almost always lose between 1.5–5 keV of the 59.5 keV interaction. This is probably due to trapping in the low field region between the lithium diffused contacts. Observations suggest that this region is ~200 microns thick in the center of the gap.

4. Discussion

The majority of gamma ray interactions in germanium between 11 and 100 keV is through photo-electric absorption by a K-shell electron. Photoelectric absorption accounts for 88% of the interactions at 59.5 keV. Of these, 54% produce a fluorescent X-ray between 9.8 and 11 keV emitted isotropically from the interaction site. The range of the fluorescent K_α X-ray (85% of the emission) is 51 microns and the K_β is 68-70 microns. A simple calculation shows that the typical range along any specific direction is approximately one third of the full range. Thus, 63% of the fluorescent X-rays are absorbed within 18 microns of the first interaction along any given coordinate axis.

The size of the initial ionization cloud after a photo-electric interaction is determined by the range of the recoil electron. The energy of this electron for K shell absorption is 11 keV below that of the initial gamma ray. The recoil electron undergoes significant secondary scattering thus rapidly losing any memory of its initial direction. The pattern of ionization left by the electron is a charge cloud with a typical size equal to the electron practical range [2]. The practical range for an electron produced by a 60 keV gamma ray is 7 microns in germanium.

Transverse electric field resulting from a gradient in the impurity concentration may be responsible for a significant lateral drift of the charge carriers. The impurity concentration in the detector used in this experiment is estimated from the depletion voltage of to be ~1.8×10^{10} cm^{-3}, with a gradient of well less than

a factor of 2 across its length. A rough estimate of the gradient in the impurity concentration is $<2\times10^9$ cm^{-3} cm^{-1}. A transverse drift field in a 10 mm thick device is estimated to be <50V. On the other hand, the gradient varies slowly in the detector, thus its local effect at any position of interaction within the detector is to add an offset the drifting charge, and not to spread it out significantly. The transverse drift field could cause up to a 0.3 mm position offset for charges that drift across the full detector thickness (1500 V cm^{-1} applied field).

The observed HWHM is slightly broader than the spatial scales of the fluorescence X-ray and variations in the initial charge cloud. Variations in transverse electric field over the length of the strip, variations in the strips themselves, and similar effects may also contribute the strip edge sharpness. Thus, the results shown in Table 1 represent an upper limit to the strip edge sharpness, but demonstrate what can be achieved in a practical device.

Other lesser effects on the edge sharpness are due to Compton and Thompson scattering. Compton scattering and Thompson scattering each account for 6% of the remaining interactions respectively. The range of a Compton scattered gamma ray depends on its energy and scatter angle. Thompson scattering in the detector and in the vacuum cover over the detector both contribute to a slight blooming of the beam used to probe the detector. This is apparent in Figures 1 and 2 as a small sensitivity in one strip while the beam is clearly over another strip.

The width of the gap between strips increases by 130 microns in Figure 1 and 110 microns in Figure 2. This difference is attributed, at least in part, to the lateral diffusion of holes and electrons as they drift ~9 mm through the thickness of the detector. The diffusion constant for holes in germanium is deduced from the hole mobility and the Einstein relation:

$$\kappa = kT\mu/e \qquad 1)$$

where κ is the transverse diffusion constant, μ is the mobility, **e** is the electron charge, and **kT** is the thermal energy. It is appropriate to use the mobility for a small electric field since the transverse field is small. The calculated diffusion constants are 230 cm^{2}s^{-1} and 210 cm^{2}s^{-1} for holes and electrons respectively. The time for diffusion is given by the distance traveled (~9 mm) and the drift velocity. At 1500 V bias this is 120 ns and 108 ns for holes and electrons respectively. A simple one dimensional diffusion calculation with the requirement that >97.5% of the charge is collected (*i.e.* >58 keV) shows that the charge spreads by 142 microns for holes and 130 microns for electrons. In theory, the cut-off for each strip should move by this amount and the gap should increase by twice this amount. The observed increase in the gap is about half of this predication, setting an upper limit on the lateral diffusion of ~130 cm^{2}s^{-1}. Energy resolution around the event selection threshold accounts for an error of ~22 cm^{2}s^{-1}.

5. Conclusion

These measurements show that lateral charge is important in the behavior of a germanium strip detector, and dominate over the size of the initial charge cloud at 59.5 keV. A practical device must consider the size of the ionization cloud(s) and an estimate of lateral charge diffusion in order to select an appropriate electrode configuration. We emphasize that the lateral diffusion is only 1% of the thickness of the device used in these experiments, and is much smaller than the gaps between the electrodes.

Charge sharing between two or more strips begins to dominate for strip pitch much finer than ~300 microns in a device like the one used here. However, this limit is similar to the size of the gap between the p^+ electrodes. In principle, finer strips may be possible in a thinner detector or a detector with a narrow gap between the strips. This applies to both the hole and electron collection electrodes. It is unlikely that the lithium diffused technology can be segmented much finer than ~1−2 mm, thus a finer pitch on the n^+ contact will require a different contact technology.

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